Uses of Solar System Resources Workshop

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MANUFACTURING AT THE MOLECULAR LEVEL. Haym Benaroya, College of Engineering, Department of Mechanical and Aerospace Engineering, P.O. Box 909, Piscataway NJ 08855-0909, 908-445-4408, (fax) 908-445-5313, benaroya@rci.rutgers.edu.

This manufacturing will be accomplished either in orbit in *micro-g* or on the Moon in *low-g*, both *hard vacuum* environments.

Two applications are currently envisioned that can have Earth, space, and lunar application:

Ultra-strong threads can be manufactured, or spun, in space or on the Moon from crystals or other composite material. Such threads can be used as structural reinforcing in mesh, lattice, and inflatable structures. They can also be used in the development of *tethers* that have been mentioned as possible sources of energy and as possible *space elevators*.

Micro-electro-mechanical devices (MEMS) are what the words say. The space/lunar environment may be ideal for manufacturing MEMS. Some of these have evolved from the SDI program. Applications are many; their manufacture provides many engineering challenges. Possible applications include *robotics*, the development of *self-replicating systems* that can be extremely useful for maintaining long-range probes and spacecraft, micro-spacecraft, micro-instrumentation, and numerous biological applications.

A LUNAR ARCHIVE: AN APPLICATION OF LUNAR RESOURCES

J.D. Burke

15 OCTOBER 1996

Vision for market: Primarily governments with some participation by foundations and the organizations they sponsor, such as universities.

Contributed by: James D. Burke, JPL and International Space University

Product and intended use: Information is sent to and stored in a robust robotic cache on the Moon, with pre-positioned facilities for its retransmission on demand to Earth. The archive is designed for human-commanded robotic access in the event of (a) a civilization-threatening disaster on Earth, (b) humans coming to live on the Moon, or (c) just historical needs after a passage of time.

Primary customer: In case (a), governments, intergovernmental agencies, or emergency authorities established after a government-eradicating disaster. In case (b), lunar inhabitants. In case (c), scholars on Moon or on Earth.

Secondary customers: Entertainment industry.

Spinoffs: Continuing development of educational and entertainment information links between Earth and Moon, toward the time when humanity becomes a two-planet species.

Economics of market: Information is the only valuable commodity that can be instantly and cheaply transferred between Earth and Moon. The cost of setting up a robotic archive on the Moon is negligible in proportion to the potential value of the stored information. However, this value remains only potential until (case a) a disaster occurs on Earth, (case b) people go to live on the Moon, or (case c) enough time passes to give the lunar archive significant historical value. Therefore, the initial investment comprising the cost of the archive and its ultra-rugged access and recovery facilities on Moon and on Earth has to be regarded as analogous to buying insurance, and any maintenance costs are analogous to paying premiums.

- Earth and/or space applications -- In case (a), retrieving the wherewithal to rebuild civilization on Earth. In case (b), providing a comprehensive local library for lunar settlers, obviating the need for them to be continually requesting data from Earth. In case (c), supplying scholars with a treasure trove from the earliest days of Earth-Moon civilization.
- Market size (annual demand, mass, form) -- Assuming case (a), the demand could take the form of a very small amount of information initially, just enough to enable an intelligent but impoverished cadre of rebuilders to begin recreating the tools needed to bring Earth's surviving population above subsistence level. This scenario (though without the concept of the lunar archive) has been treated in several science-fiction classics, notably Refs. 1,2 and 3. A few megabytes should be enough for the initial stage. The mass transmitted is of course near zero.

Careful thought is needed as to the form of this first transmission, since one has to assume very limited surviving technology at the receiving end of the link. What could a modern Robinson Crusoe build or unearth that would enable the first post-disaster access to the lunar archive? A radio receiver with a hand-erected antenna and a hand-cranked generator to receive a continuously repeating, uncommanded broadcast? How would bootstrapping proceed from that to a system on Earth powerful enough to call up the archive and demand specific information from it? How would the very first instruction set be stored on Earth? Is a retrodirective radio phased array a possibility? Or could the first contact be optical, for example by a system with transmitter and receiver on the Moon and retroreflector on Earth? Regardless of these technical tradeoffs the initial 'market' is, in case (a), tiny but of enormous value, justifying large investments to reduce the risk of not making the first contact. Among these investments would be redundant and very robust protection of the initial receiving tools, with treasure-hunt clues provided so survivors could find and deploy them.

In case (b) the annual information demand would be comparable to that of a Carnegie library in a small city. The 'market' would not be expected to repay the cost of setting up the library, but users could be asked to pay small fees to compensate for maintenance costs.

In case (c) the concept of a market is irrelevant. Access by scholars to information is a public good, sponsored either publicly or privately in the interest of advancing knowledge. Note that this principle is, at least with respect to information stored electronically in databases, now under attack for several reasons and the lunar archive would presumably be no exception. It would be interesting, would it not, if the lunar settlers were to decide to ignore these terrestrial disputes and adopt some different legal framework for dealing with this question? In that event the lunar archive could assume value as a precedent, beyond its intrinsic importance.

• Delivery time required by customer -- In case (a) the time requirement depends on the nature and severity of the terrestrial disaster. With civilization obliterated by an asteroid or comet impact and agriculture in a worldwide state of collapse, the immediate delivery of some megabytes from the archive might not do much good since the human survivors, if any, would be preocccupied with hunting and gathering. But with a less severe impact such as the worldwide failure of electrical generation and distribution or the breakdown of civil societal controls (as treated in Refs. 1 and 2 respectively), prompt access to the lunar archive (in a matter of weeks or months) could be critically important not only for its technical and tool-building purposes but also as a generator of morale, hope and discipline for the future. In Ref. 1 these good human traits did recover even though advanced technology was, for the foreseeable future, lost. In Ref. 2 some technology survived but the return of a civil society was delayed. In Ref. 3 both technology and law were recreated but in vastly altered forms.

In case (b) the time requirement is paced by the build-up of the lunar population. As soon as even a few people are in residence on the Moon, it will be important for both technical and social/psychological reasons to have a functioning library there. There is no reason why this should not also serve as the emergency archive for Earth.

In case (c) the delivery time required is of the order of decades after emplacement of the information on the Moon. In all three cases there is a requirement for multi-decade storage with reliable retrieval.

• Target product price -- In case (a) the concept of a price is irrelevant since there may be no functioning economy on Earth. In case (b) the subject of price has been mentioned earlier above. A modest charge, analogous to what is now demanded for public database access, could be assessed to cover maintenance costs. In case (c) a price could be negotiated individually with historical researchers, based on need and ability to pay, for example via grant funding. In none of these instances would the price be expected to cover the whole cost of setting up the database and its containing, cataloguing and transmitting facilities.

• Principal competitor -- Secure storage on Earth. In case (a) it can be argued that placing an archive on the Moon gives little advantage over an asteroid-impact-proof network of deeply buried, redundant archives on Earth. In case (b) it can be argued that the contents of a lunar library could be sent to lunar settlers on demand from Earth. In case (c) it can be argued that a set of time capsules on Earth would provide the same information source for future scholars.

Should humanity get serious about the asteroid/comet impact hazard, it is obvious that both the lunar archive and its main competitors should be implemented.

• Non-economic benefits -- The chief benefit of the lunar archive is non-economic. In none of the three considered cases can the data be sold for more than the system's cost. The archive represents an investment by humanity in its future. In a pessimistic scenario it offers prompt post-disaster recovery of human culture, wisdom and wealth. In an optimistic scenario it offers a beacon toward humanity's becoming a multi-planet species. In a neutral scenario it offers another way for civilization to sustain and hand down over generations the knowledge and wisdom of forbears.

• Production objectives -- Annual storage accumulation should be comparable to that of a large institution such as the Library of Congress, for at least the first several years after the storage system is robotically emplaced on the Moon. During the prior period of several years while the system goes from concept, through selling, to approval, design and execution, a low-cost, primarily theoretical project should be in progress to select the highest-priority information to be stored first and to develop the concept of initial access and bootstrapping. Publication of the early conclusions of this effort would probably cause controversy. That could be good, both as a source of publicity and as a stimulant of diverse ideas.

• Special quality constraints -- Present techniques for testing and maintaining database integrity are sufficient for the purposes of the lunar archive. However, this particular archive has one unique requirement: It must be retrievable and at least its first bootstrapping information must be understood by any possible human user independent of language or culture. Not only the information stored on the Moon but also the initial instruction set, ruggedly protected on Earth, must meet this need. Thus something analogous to the Rosetta Stone must be a part of the system.

• Technology needs and maturity -- The technology for robotic transport to and installation on the Moon can be considered available now, with future advances concentrating on reducing cost. However, in all three cases (a,b and c) the archive generates a need for very long unattended lifetime, perhaps analogous to remote, solar-powered weather stations or undersea cable repeaters on Earth. The tradeoff between design for long life and design for robotic repairability will differ from subsystem to subsystem but, at least for case (a), the disaster scenario, the first bootstrapping contact must be made extremely reliable and redundant, to a degree resembling the reliability of systems that have prevented unauthorized launch of nuclear weapons until now. Technology and design concepts for achieving such high assurance will need new development, and no complete proof test is possible.

• Planetary materials required -- The primary resource needed is simply a location far enough from Earth to make the archive immune to a civilization-destroying disaster. Why should the archive be on the Moon? The main reason is to take advantage of the Moon's stability as a platform having no failure modes. The lunar robotic system be emplaced at a lunar pole. With continuous solar power available and an unchanging thermal environment (except for occasional eclipses) at a pole, the archive should need little tending during its indefinite period of sleep before going into action. As stated above the system should emit a continuous broadcast of the first bootstrapping information to obviate the need for initial commanding from Earth. Lunar materials could be used to support the emplaced devices, for example to shield against meteorite impacts, but the mass of material required would be quite small, perhaps a ton at most. Solar power (with energy-storage backup for eclipses) should be used to provide indefinite life.

• Manufacturing and production -- the primary product, information, would initially be gathered entirely on Earth. After establishment of a functioning human society on the Moon the database content could of course be supplemented by the creative product of the lunar settlers. The degree of automation for data entry and retrieval is an interesting subject for study: Obviously the total database input would eventually become far too large for direct human entry by speaking or typing, so some form of document scanning or digital transfer is required. However, the initial bootstrapping information could be a small enough package for direct human entry, and in any case this information is so critical to the entire concept that it should be closely reviewed and its integrity periodically checked by direct human intervention. In the more severe disaster scenarios of case (a), one has to assume very limited surviving automation on Earth, so direct readout to humans, independent of language, would be required at least for the first recovery stages.

• Power requirements -- To keep the initial receiving equipment simple it will probably prove optimal to have a fairly high effective radiated power delivered to Earth. For a radio system this means a fixed high-gain antenna on the Moon with a half-power beamwidth of more than ten degrees to cover the entire Earth plus Earth's apparent movement due to lunar libration. Transmitter power should be at least a few watts. Thus the raw power input from a solar array should be in the tens of watts. For simplicity and reliability a Sun-tracking array should probably not be used; instead the array would be a cylinder aligned with the Moon's polar axis, with enough array area to generate several tens of watts (plus some area for redundancy) regardless of the Sun's azimuth. Heat rejection would be by a radiator in a shaded place, facing dark space. Once installed the system should be essentially passive with no moving parts on the Moon.

REFERENCES

1. Stewart, George R. Earth Abides. New York: Ballantine Books, 1976
2. Brin, David. The Postman. New York: Bantam Books, 1986
3. Miller, Walter M. A Canticle for Leibowitz. Philadelphia: Lippincott, 1960

A CONCEPT FOR A SPACE INDUSTRIAL PARK. Brad Carpenter, Office of Life and Microgravity, Sciences and Applications.

Human Exploration and Development of Space

What is a Space Industrial Park? A Space Industrial Park provides infrastructural support to commercial enterprises seeking to establish operations in extraterrestrial environments.

Required Support:

Transportation (sine qua non)

Initially NASA will be the primary provider, and will have to provide "AAA service" beyond the period when access to space is commercially available

Legal Framework

Property Rights
Criminal and Civil Law
Tax Structure
Regulatory Environment (Building Codes, Environmental Regulations, OSHA...)
Beyond the scope of my experience, but clearly essential for private investment. One certainty regarding the future is the existence of lawyers. Enterprises will need to understand their risks before committing capital.

Required Support, ii:

Life Support

Oxygen
Water
Food
Waste Management
Medical Care
Consolidation of the primary and/or backup life support logistics and medical support for enterprises will lower cost and improve reliability.

Technology

Surface Operations
Construction
Power
Process Operations
Availability of technology for extraterrestrial processes is likely to be one of the most important barriers for commercial enterprises. The cost of research and development to establish commercial enterprises will depend on access to basic knowledge regarding space engineering.

A Foundation for Industrial Development

Resource Utilization Technologies:

Noble metals from asteroids
Helium-3 production
Oxygen for propulsion, exploration, and development
Fabrication of construction materials
Production of Photovoltaic devices
Solar dynamic power generation

Require Process Operations:

Materials Handling
Size Reduction and Enlargement
Adsorption, Extraction and Refinement
Heat Transmission and Transfer
High Temperature Processing
Chemical Reaction Engineering

Which will all be different in non-Earth environments

Process Research for In-Space Operations

Development of a knowledge base that will enable the results of two centuries of Earth-based technology development to be extended into space is one of the most significant legacies that we can provide for the future of space development. The requirements for technology in space development can be satisfied in the future with the evolution of numerical simulation and the advance of scientific knowledge, if we implement a program of research focused on critical unknown issues.

The Space Industrial Park will require this knowledge base as a virtual environment to provide the tools of earth-based technology for space development.

Potential Research Areas

Chemical reactors/Extraction processes and techniques
Advanced power systems
- High power density
- Highly reliable systems

Propulsion systems
- Integrating *in situ* resource utilization system design
- Investigation of using alternative propellants

Cryogenic storage
Processing plant operations and maintenance - operations from Earth
Surface systems operations - diggers & haulers
Metal joining and fabrication technology
Construction material technology
...and many others yet to be identified

LUNAR SOLAR POWER SYSTEM. David R. Criswell, Director, Institute for Space Systems Operations, SR1, Suite 504, University of Houston, Houston TX 77204-5505, 713-743-9135, (fax) 713-743-9134 or 281-486-5019 (phone and fax), dcriswell@uh.edu.

VISION FOR MARKET:

Market:
1. Increase supply of commercial electric power on Earth.
2. Enable high-power electric vehicles and facilities on the moon and in cis-lunar space and beyond.

Product (Describe Product and Its Intended Use):
1. Load-following electric power delivered via microwaves to commercial scale utility-receivers on Earth, in space, and on the moon.
2. This electric power will be used to produce constructed resources, up-grade natural resources, and power the activities of humanity.

Primary Customer (Who Will Utilize the Product?):
1. Utilities and large industrial complexes on Earth.
2. Industrial facilities on the moon and in cis-space.

Secondary Customer (Spin-Offs, Byproducts, etc.):
Population of Earth:
1. Accelerate world economic growth by providing low-cost electric power.
2. Enable the creation of material wealth from common resources and the efficient recycling of manufactured resources.

Population Off-Earth:
1. Provide jobs on the Moon and in cis-lunar space associated with construction and maintenance of the Lunar Solar Power System.
2. Enable more aggressive development and exploration of the solar system for the benefit of mankind.

ECONOMICS OF MARKET:
Earth:

Market Size:
1. Minimum annual demand is 2 kWe per person on Earth or 20,000 GWe by the year 2050. For electricity sold at 0.03 $/kWe-h this corresponds to a world market of approximately 6,000 B$/Yr.

2. The significant secondary product is faster economic growth. OnekWe-h of energy is associated with 1 to 2 dollars of gross products. Thus, 20,000 GWe-Y/Y potentially enables 180 T$/Y to 360 T$/Y of gross world product or for 10 billion people this is up to 36,000 $/person. By comparison, the present GWP/person ~$4,000.

3. Physical measures:

   Volume - Not applicable.

   Mass - 20,000 GWe-Y/Y corresponds to the complete conversion of 7.01 tons/Y of mass to energy.

   Form - Input power to Earth is low intensity (10 to 250 W/m2) microwaves (~10 cm wavelength) in the form of closely collimated beams.

Delivery time required by customer: There is an immediate and growing worldwide need for low cost electric power.

Target product price: Approximately 0.03 $/kWe-h.

Principal Competitor: At the scale of 20,000 GWe, and above, and at a cost of 0.03$/kWe-h or less there are no competitors. Nuclear breeder reactors can supply this level of power for approximately 2 to 3 centuries from terrestrial resources but at a higher cost. Thereafter costs will rise because the nuclear fuels must be extracted from sea water and minerals such as granite. Fusion reactors (D-T, 3He, etc.) may eventually provide commercial power. However, barring less demanding conversion technologies, the power will be more expensive than from LSP.

Space Applications:
Market Size:

1. The primary initial market will be the LSP manufacturing operations on the moon and the associated space transportation and logistics systems. During the construction phase these systems will utilize approximately 10 GWe. Thereafter the LSP Systems needs will decrease significantly.

2. As manufacturing capacity increases on the moon and in LO and EO the manufacturing facilities can provide propellants, life-support chemicals, structures, and other components to build facilities on the Moon and in cis-lunar space and to operate them. The following numbers assume that 90% of the mass of a large LSP installation system is made from lunar materials and 1980s levels of technology are assumed in the various manufacturing processes and LSP components (Criswell and Waldron, IECEC900279).

3. Physical Measures

   Volume - of habitats and facilities for manufacturing, repair, and maintenance produced over the first ten years is approximately 200,000 m3/Y.

   Mass - Production on the Moon of ~50,000 tons/Y.

   Form - Habitats, excavation and beneficiation machinery, emplacement machinery, glass melting and forming machinery, assembly machinery and enclosures, etc.

Delivery time required by customer: Coincident with start of LSP emplacement on the Moon.

Target product price: Significantly less than Earth-to-Moon transportation costs (¾ 10,000 $/kg).

Principal Competitor: Nuclear power and solar photovoltaic systems taken to the Moon.

NON-ECONOMIC BENEFITS (e.g., Environmental):

1. Eliminate environmental damage associated with the present means of generating commercial electric and thermal power.

2. Eliminate the political and economic tensions associated with limited primary energy resources on Earth.

3. Establish major industrial and operations capabilities on the Moon, in LO, in EO, and through major portions of cis-lunar space.

4. Demonstrate the practical support of human life without utilization of the biosphere.

5. Enable deployment of permanent major research facilities throughout the solar system and safe and relatively low-cost space transportation.

Production Objectives: Annual production rate at expected market penetration: Approximately 500 GWe/Y over 40 years.

Special Quality Constraints: The LSP System enables and establishes new markets for electric power that can not be serviced by other options (coal, oil, nuclear, terrestrial renewables). Fuel coal and hydrocarbons become available as petrochemicals for rapidly growing markets.

TECHNOLOGY NEEDS AND MATURITY:

Identify Technology Development:

* The LSP System, restricted to direct transmission from the Moon to the Earth, is composed of devices and systems that are at the NASA Technology Readiness Level (TRL) = 7 or greater (Criswell IAF 96 R.2.04).

* Microwave redirectors (reflectors or retransmitters) in orbit about Earth can significantly decrease the cost of a stand-alone LSP System by directing beams to rectennas that can not view the Earth. This decreases the need for costly power storage or supplemental power generation on Earth. Reflectors now TRL ~2. Retransmitters are now TRL ~5 to 6.

* Solar Reflectors in orbit about the moon can direct sunlight to lunar power bases that are not directly illuminated or are eclipsed. Solar Reflectors are TRL ~2.

Cost Reduction Requirements: The mature LSP System provides commercially competitive power even if implemented with 1980s levels of technology (Criswell and Thompson, Solar Energy, 119-131, 1996).

The up-front and life-cycle costs can be greatly reduced. There are several cost reduction strategies.

* Increasing the overall efficiency of the LSP System sharply decreases the physical size of the lunar installations and thereby the life-cycle costs (refer to Criswell IECEC 95-23).

* Use of lunar materials to bootstrap the lunar production facilities can potentially greatly reduce up-front costs and life-cycle costs (Criswell, Space96).

* The LSP System up-front costs drop by 80% or more if the first demonstrations are done in the context of a large manned lunar base (Criswell and Waldron, Acta Astronautica, 469-480, 1993).

* Net costs can be decreased by beginning with a demonstration emplacement facility (~30 to 100 GWe installed over 10 years) and then shifting to full scale production funded from the sale of power on Earth.

PLANETARY MATERIALS REQUIRED:

Source location: Over 99% of the materials are lunar derived.

Type of material: Bulk soils, soils separates, iron, silicon, oxygen.

Amount of material to be mined annually: During the full scale production phase (500 GWe/Y) over 30 years the major mass handling operations are:
Mining and scrapping - 2 108 tons/Y
Beneficiation - 1 109 tons/Y
Others (glass, etc.) - 5 107 y tons/Y

These numbers decrease sharply with increases in overall system efficiency (Criswell and Waldron IECEC 900279; Criswell Space96).

MANUFACTURING AND PRODUCTION:

Refining location: Moon
Assumed degree of automation: High
Manufacturing location: Two or more locations on opposite limbs of the Moon as seen from the Earth.
Assumed degree of automation in space: High

POWER REQUIREMENTS:

Peak level: During manufacturing and emplacement at 500 GWe/Y the processes consume approximately 10 GWe and considerably greater solar thermal power for glass forming on the Moon and in LO.

Steady state level: Less than 1 GWe.

PRODUCTION OF PHOTOVOLTAIC SYSTEM MANUFACTURING SYSTEMS FROM LUNAR MATERIALS. Michael B. Duke, Lunar and Planetary Institute, 3600 Bay Area Boulevard,Houston TX 77058.

VISION FOR MARKET: A growing demand for power from space and in space requires rapid growth of manufacturing capability for photovoltaic systems in space.

PRODUCT: Manufacturing systems, capable of producing photovoltaic systems from lunar materials. Manufacturing systems will include furnaces, reactors, raw and finished material transporters, thermal and electrical power systems, radiators, structures, shielding, pressurized volumes, material storage tanks, etc.

PRIMARY CUSTOMER: Manufacturers of space power systems.

SECONDARY CUSTOMER: A wide range of other manufactured items will be producible on the margin of the main product line.

ECONOMICS OF MARKET:

Earth and/or Space Applications:

A goal for a manufacturing system capable of producing 10 tons of finished product per year is 1 ton of system hardware.

The efficiency of production will increase with the scale of production.

Market Size: A 5 GWe photovoltaic system on the Moon may have a mass of 50,000 tons. Thus, if it is to be produced in a year, it will require 5,000 tons of production hardware. It is assumed that a maximum rate of production of 5GWe photovoltaic systems will be 200 per year, after 20 years, so 10 systems are required per year. This is a mass of 50,000 tons.

Delivery Time Required by Customer: On contract, delivery time requirements are on the order of 2-3 years.

Target Product Price: Each fully functional production system, capable of producing a 5GW power system in a year for 20 years, will have an estimated economic value of $400 Billion; The target product price for each production unit is $20 billion.

Principal Competitor: Products manufactured on Earth and emplaced in Earth orbit.

NON-ECONOMIC BENEFITS: Will lower the cost of production so far that many other activities will be enabled, for example power-beaming systems for electric propulsion vehicles operating in the inner solar system.

PRODUCTION OBJECTIVES: 50,000 tons of varietal hardware and systems per year

TECHNOLOGY NEEDS AND MATURITY:

All systems can be fabricated now on Earth
Materials processing systems need to be adapted to lunar environment
High degree of automation, reliability, self-maintenance and repair are required
Integration of a variety of subsystems into a efficient functioning system at these (relatively small) production levels is a major challenge.

PLANETARY MATERIALS REQUIRED:

Source location: Moon
Type of material: Principal metals and non-metals in basaltic and anorthositic rocks and soils; extraction of volatiles as byproducts for propulsion systems.
Amount of material to be mined annually: (Assuming that 10% of material mined is utilized), 500,000 tons of material to be mined and processed (250,000 m3, or 500mx500mx1m)

MANUFACTURING AND PRODUCTION:

Refining location: Moon
Assumed degree of automation: High
Manufacturing location: Moon
Assumed degree of automation (if in space): High

POWER REQUIREMENTS:

Peak level: 250 MW
Steady state level: 250 MW

HUMAN SUPPORT REQUIREMENTS:

Personnel on Moon: 100
Personnel on Earth: 1000

COPRODUCTION OF METALS AND OXYGEN FROM LUNAR RESOURCES. STTR Contract NAS 9-19596, Rudolf Keller and David B. Stofesky, EMEC Consultants, 4221 Rountop Road, Export PA 15632, (412) 325-3260, Kumar Ramohalli, University of Arizona, Tucson AZ 85721.

ELECTRICAL CONDUCTORS FROM LUNAR RESOURCES

	Fe	Al	Ca
Resistivity (μ ohm cm)	9.71	2.65	3.91
Conductivity ($ohm^{-1}\ cm^{-1}$)	1.0×10^5	3.8×10^5	0.26×10^5
Spec. Mass ($g\ cm^{-3}$)	7.86	2.70	1.54
Conductivity Per Mass ($ohm^{-1}\ cm^{-1}\ g^{-1}$)	1.3×10^4	1.4×10^5	1.7×10^5
Energy to Produce (ΔH_{25C} in $kJ\ g^{-1}$)	4.87	31.0	15.8
Conductivity Per Energy to Produce ($ohm^{-1}\ cm^{-1}\ J^{-1}$)	2.67	4.52	11.2

FACTORS FOR EVALUATION

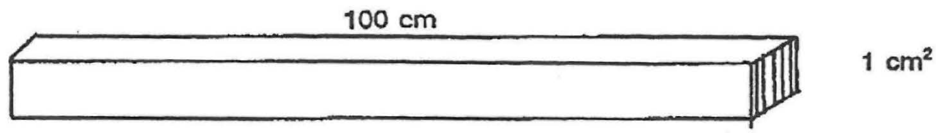
Lowest Energy Consumption: ==> Ca

Ease of Raw Material Preparation: ==> Fe

Ease of Fabricating: ==> Al

CONSIDERATION OF ELECTRICAL ENERGY REQUIREMENTS

Al

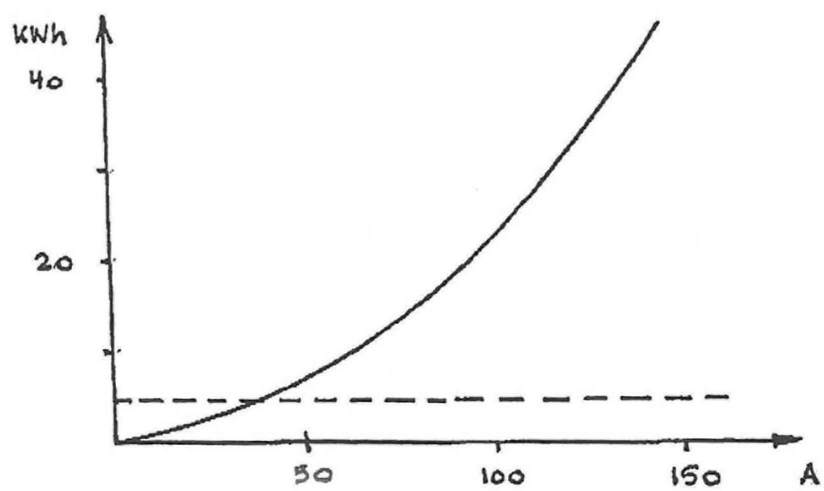


TO PRODUCE CONDUCTING MATERIAL: **4.24 kWh**

(at 16 kWh/kg)

SUPPLY OF OHMIC LOSSES: **23.2 kWh yr^{-1}**

(at 100 A, full time)



PHOTOVOLTAIC ARRAYS FROM LUNAR OR ASTEROIDAL MATERIALS. Geoffrey A. Landis, Lewis Research Center (from TM-102102)

1. Introduction

A first step toward realization of a lunar manufacturing base is to identify near-term products that could be manufactured on the moon for cost-effective use on-site and elsewhere. We discuss manufacture of photovoltaic solar arrays as one such product. A lunar base is projected to require 100 kW to 1 MW or more of power, and amining and manufacturing facility considerably more. It is a natural assumption to require that a manufacturing facility produce from locally available materials the solar arrays for its own expansion in a "bootstrap" process. Once it is accepted that a lunar base may manufacture its own power source, it is a straight forward extrapolation to the lunar production of solar arrays for other uses, taking advantage of the greatly reduced transportation costs due to the lower escape velocity of the moon. The widely discussed manned Mars mission, for example, could require 1 MW or more. Transportation costs alone for a Mars power source could be on the order of a billion dollars. While these costs can be projected to decrease with the future availability of advanced launch systems and use of in-situ propellant production, the possible economic gains are nevertheless extremely large. This is a strong incentive for seeking ways of lowering transportation costs for the solar arrays. One route to doing this is to increase the array (and storage system) power to weight ratio ("specificpower"). Another possibility is to manufacture the arrays in space.

2. Lunar Photovoltaic Arrays

Most current plans for a lunar base assume that the base will include an industrial facility, primarily to produce oxygen for propulsion systems by reduction of the lunar soil [1]. A second product for such a facility could be solar arrays. While the primary user of lunar- produced solar cells would undoubtedly be the lunar base itself, there would be many markets. Figure 1 shows some of these possible uses of lunar produced photovoltaics, including solar-electric propulsion for orbital transfer vehicles and for solar system exploration, and power systems for geosynchronous Earth orbit (GEO) and low Earth orbit (LEO) satellites.Use of lunar-manufactured solar cells for high-power solar-electric propulsion is an especially attractive option. Recent proposals for a manned Mars mission [2], for example, propose an unmanned, electric-propulsion cargo vehicle to ferry supplies to Mars orbit inadvance of the crew on a low-thrust orbit. The power system for the electric propulsion is a 5 MW nuclear generator, which could be replaced with lunar-manufactured thin-film solar cells for a considerable savings in required weight to orbit. For a "sprint" mission, a high-power electric propulsion vehicles of 200 MW power and a specific impulse of 20,000 sec could make the round-trip to Mars as short as 7.5 months [2].Solar-electric transport vehicles would also greatly reduce the required mass for servicing the lunar base itself. B.G. Logan [3], for example, proposes a 6 MW Manned Lunar Shuttle powered by a pulsed plasma gun, estimating that this could halve the transport costs, even for relatively modest specific power solar arrays. Use of lunar material has also been widely proposed for manufacture of solar cells for satellite solar power stations [4]. The cost of transportation from the Earth's surface to orbit and beyond can be quite high. Figure 2, for example, shows the cost of delivering conventional and advanced power systems to orbit, the moon, and Mars, usingcost estimates typical of current technology space boosters. For example, a one-megawatt power system delivered to Mars could have transportation costs alone in the ten to hundred billion dollar range. While these costs are likely to be decreased with advanced transportation, they are likely to remain high.

The advantage of lunar manufacture is that the escape velocity is only 22% that of the Earth. Escape velocity from asteroids is even lower. Table1-A shows the V (velocity increment) needed to achieve various destinations from the Earth's surface and from the moon. The payload fraction decreases exponentially with the delta-V, and a much higher fraction of the lift-off mass can be useful payload, as shown in Table 1-B, which shows the theoretical maximum fraction of lift-off mass which can achieve the listed orbit if launched from the Earth's surface, compared to launched from the moon. (Actual rockets never achieve these values; typically only 1–2% of the mass of a rocket launched from the Earth isuseful payload.) Even to low Earth orbit, five times the payload can be delivered if launched from the moon than if launched from the Earth's surface. For the commercially valuable geosynchronous orbit, almost nine times the payload can be delivered. This is a strong leverage factor for lunar manufacture. The design criteria for lunar manufactured solar cells depends on the mission. The most important criteria for most missions are maximum power/weight ratio (specific power) and minimum usage of materials transported from Earth. For use on the lunar surface, specific power is not an important criterion.

Vision for Market: Solar arrays manufactured from lunar or astroidal material could be used for every application requiring power in space, including commercial satellites such as communications and mapping/resource satellites, and future space missions.

Product: Solar Arrays in space

Primary Customer (Who Will Utilize the Product?):

(1) existing commercial customers: communcations satellites, resource satellites
(2) new commercial customers: solar electric propulsion "tugs" to emplace satellites, space manufacturing facilities
(3) space mission customers: Earth orbital stations (International Space Station and derivitatives), Mars mission

Secondary Customer (Spinoffs, Byproducts, etc.):

(1) satellite solar power systems which beam power across space and to ground users
(2) advances in solar cell manufacturing which can be applied to Earth
(3) products of space manufacturing facilities which require high power

Economics of Market:

Earth and/or Space Applications: Market size (identify annual demand for primary and significant secondary products, volume, weight/mass, and form):

(1) existing commercial customers: about 50 kW/yr currently, could be 500kW/yr in near future
(2) new commercial customers: several MW/yr
(3) space mission customers:

Earth orbital stations: 100 kW, replaced approximately every 10 years, currently, potentially two or three times this in future Mars mission: one-time requirement of 100 kW to several MW

Delivery time required by customer: year 2000 plus
Target product price: current product costs $1000 per watt exclusive of deliver to space.
Principal competitor: Terrestrially manufactured product

Non-Economic Benefits (e.g., Environmental): Toxic and dangerous manufacture steps moved to space.

Production Objectives:

Annual production rate at expected market penetration: 100 kW/year
Special quality constraints:

Technology Needs and Maturity (Identify Technology Development or Cost Reduction Requirements): Needs research into best way of refining raw materials; a baseline technology is proposed.

Planetary Materials Required:

(1) Source location: moon or asteroids
(2) Type of material: regolith
(3) Amount of material to be mined annually: hundreds of kilograms
(4) Hydrogen is also a desirable material, and would require either refining large amounts of lunar soil for solar implanted hydrogen, or location of water source in space at polar caps or from carbonaceous asteroids

Manufacturing and Production:

Refining location: moon
Assumed degree of automation: TBD
Manufacturing location: moon
Assumed degree of automation (if in space): TBD

Power Requirements:

Peak level: many kilowatts to 1 MW
Steady state level: many kilowatts

Table 1-A. delta-V in km/sec (minimum velocity change needed to launch payload).

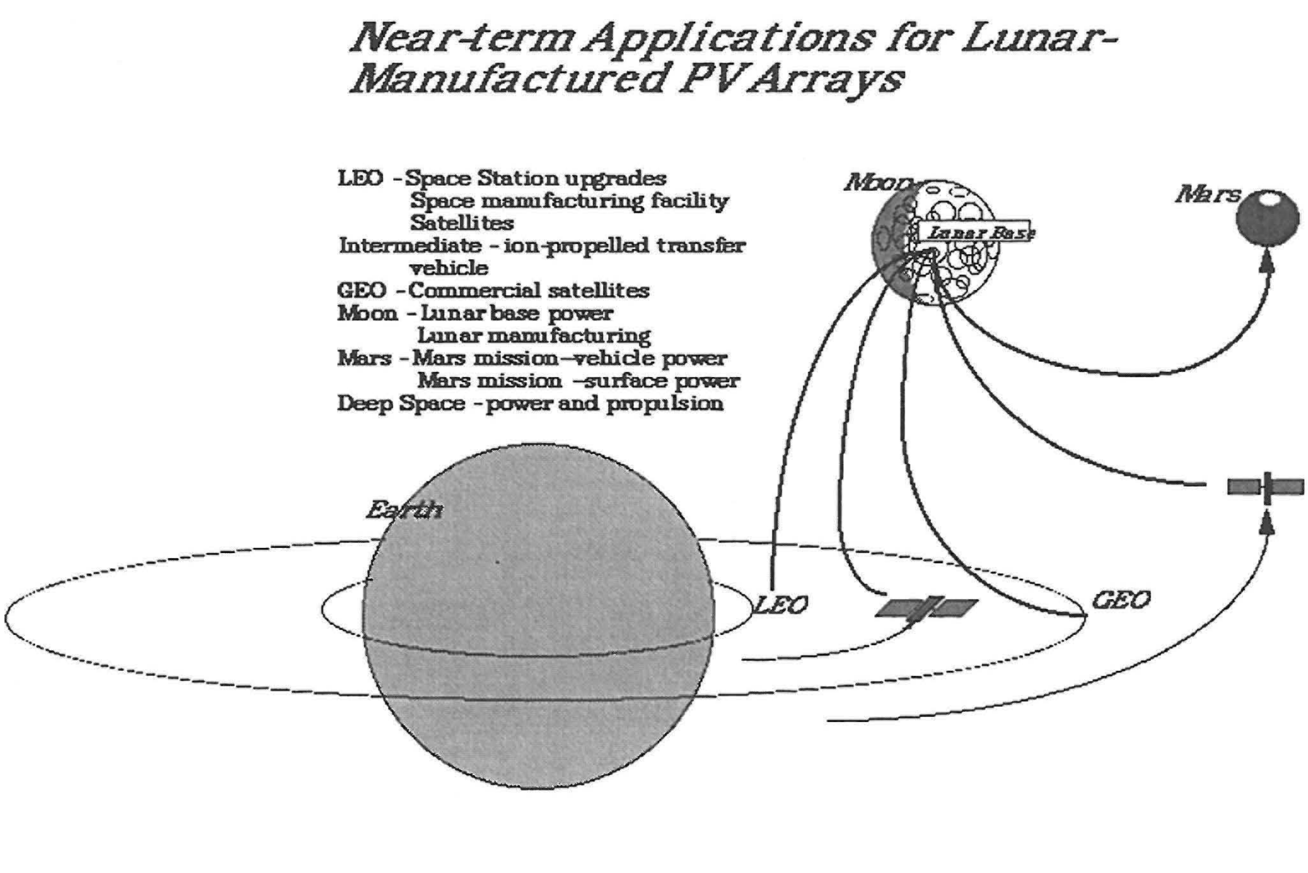
	From:	
To:	Earth	Moon
L.E.O.	9.3	3.3
G.E.O.	11.9	3.2
Moon	13.6	-
Mars transfer orbit	13.6	5.2

Table 1-B. Theoretical Maximum Payload Fraction (in percent).

	From:	
To:	Earth	Moon
L.E.O.	9.8	43*
G.E.O.	5.1	45
Moon	3.3	100
Mars transfer orbit	3.3	27

Calculated using Vexhaust = 4 km/sec (H_2/O_2 propellant).
* Assumes aerobraking at perigee.

Figure 1.



MULTIBAND-GAP HIGH-CONVERSION-EFFICIENCY CONCENTRATOR SYSTEM.

Neville I. Marzwell, Jet Propulsion Laboratory, Pasadena CA 91109

Abstract: The concept is to use lowest cost semiconductor space material and fabricate a combination of solar cells with different spectral responses to match the spectral responses of the sun (visible and IR). Spectral power dispertion can be achieved with a prism, a fresnel lens or a Fabre-Perot filter. The different spectral responses could be achieved by doping the semiconductor material based on voltage-matched structure validated technology in which the cells are interconnected at the module level. Many individual cells of the same band gap are electrically wired together into a series string. The individual series strings are then electrically connected in parallel. Such strings are produced for several different band gaps which are expected to yield efficiencies greater than 50% under one sun AM0 (space illumination).

Proposed Effort Phase II
Principal Investigator: Paul Stella

Phase I Principal Investigator: Carol Lewis, Jet Propulsion Laboratory

1. Introduction and Background

A major factor limiting the efficiency of single junction solar cells is that they can utilize only a limited region of the incident solar spectrum. In contrast, multijunction cells, with appropriately spaced subcell band gaps, offer a very attractive method to utilize a much larger fraction of the incident solar spectrum. To date, stacked multijunction cells have shown conversion efficiencies as high as 30% under 100 suns AM0 (space illumination). Here we propose investigating a combination of a solar concentrator, spectrum splitting filters, and solar cells optimized for complementary spectral regions, in order to convert over 50% of the incident solar energy to electricity. We propose to use a voltage-matched structure [1], in which the cells are interconnected at the module level. First, many individual cells of the same band gap are electrically wired together into a series string. Such strings are produced for several different band gaps. The individual series strings are then electrically connected in parallel. This differs from stacked multijunction cells being developed by industry, where two to three subcells of different band gap are connected together into individual stacks. Key advantages of voltage matching include the following: Each cell is individually optimized and can operate at its maximum power point. A larger number of different band gaps can be used in order to maximize utilization of the solar spectrum. In a stacked multijunction system, the number of band gaps is typically limited to three or at most four. Power conversion is simplified, since each individual string provides the same voltage. It is significantly easier to process several strings of different current at the same voltage, compared to processing several strings of the same current at different voltages.

2. Objectives and Scope

The objective is to provide a low cost method to utilize a combination of solar cells with different spectral responses. This is expected to yield efficiencies greater than a factor of two higher than those attainable with current high efficiency concentrator single junction cell systems. It will provide a small area, low stowage volume photovoltaic (PV) system which is optimized for use with small spacecraft. The work will build upon the results of a preliminary multibandgap concentrator systems study conducted by these investigators in 1995.

3. Technical Approach

Task 1. Determine temperature and intensity impacts upon current-voltage (I-V) characteristics for individual cells and for the complete system.

Task 2. Evaluate spectral power focusing /collection techniques on the candidate cell materials.

Task 3. Determine the optimum optical element geometry and configuration, and determine the impact of concentration ratio upon cost.

Task 4. Based on the results of tasks 1–3, develop an end-to-end trades model, to be used to optimize mass, cost, efficiency and power for different requirements.

4. Schedule

The proposed work would begin in January 1996 and be completed by the end of December 1996. The product will be a detailed study report and design recommendation for a high efficiency solar power collection and conversion system.

5. Resources

The proposed work would require a total of $100 K over twelve months.

6. Proposed Follow-On Schedule and Resources

Near-term deployment, including hardware fabrication, would be addressed in a follow-on Phase III with cells of two to three different band gaps. The proposed cost of such follow-on work, beginning in 1997, would be $450 K over eighteen to twenty-four months. Subsequently, the system would be demonstrated with progressively increasing numbers of complementary cells.

References: [1] The voltage matching concept was originally developed by James Gee of Sandia National Laboratories: James M. Gee, Voltage-Matched Configurations for Multijunction Solar Cells, Proc. 19th IEEE Photovoltaic Specialists Conf., p. 536 (1987).

UTILIZATION OF COLD-TRAPPED COMETARY VOLATILE MATERIAL. Dr. Stewart Nozette, USAF, Clementine II Program, 711 N. Fayette Street, Alexandria VA 22314 (703) 739-8855 (703) 684-0672, (fax), Email: nozette@msti3.com.

The Clementine 1 mission obtained evidence of frozen volatiles cold trapped at the lunar south pole. This evidence was obtained through imaging which revealed the extent of permanently shadowed regions at the lunar poles, and bistatic radar which measured a polarization reversal localized to the lunar south pole region. This polarization reversal has the characteristics of the Coherent Backscatter Opposition Effect (CBOE) which requires a low loss volume scattering target. Geologically common low loss materials include ices and sulfur. Metallic surfaces and geometric arrangements of rocks do not give rise to CBOE. If it is assumed that the source of this material is cold trapped cometary volatile material, then water ice is a likely major constituent. From a resource perspective this is an important find. The quantity of volatile material present can be estimated assuming it has a radar cross section similar to that measured for the polar deposits on Mercury. Using this assumption the Clementine bistatic radar data (supported by Arecibo observations) suggest a total volatile mass on the order of 10E 15 gm. This estimate is consistent with Arnold's 1979 10E 16 gm estimate of water mass which could be cold trapped. If this material is cometary it suggests that even minor cometary constituents may exist in very sizable and exploitable quantities. The minor constituents such as CO_2, NH_3, CH_4, and noble gases (Ar, Xe, Kr) would also have very important uses. For example, the commercial communications satellite industry is very close to deployment of Xe based plasma thrusters. A solar electric Xe fueled Earth/Moon vehicle would greatly improve the economics of lunar base development, allowing for flexible transportation between LEO and LLO. Lunar derived chemical propellants can perform the lunar ascent/decent maneuver, allowing for a totally lunar fueled transportation system from LEO. A Xe propellant also negates the problems of microgravity propellant transport, aerobraking at Earth, and long duration cryogenic storage. The lunar ascent/decent vehicles can be fueled in a gravity field and off load payloads from the tug only when it arrives in LLO, negating the requirement for long duration cryogenic storage. The Xe can be placed in predeployed tank pallets and is much easier to handle than cryogenic O_2 and H_2. Payloads can also be palletized allowing for simpler teleoperated manipulations.

It is important to establish the quantity and composition of these putative resources prior to extensive system design of a lunar base, as the existence of readily exploitable volatiles will have major impacts on system design approaches and overall program economics. For this reason the location, distribution, and composition of polar volatiles is of vital importance to lunar base planning and development. Lunar Prospector, if successful, can confirm the existence of cold trapped volatiles. However, the resolution obtained will be inadequate to provide the detailed information required for exploitation. It is proposed that a follow on orbital/penetrator mission, followed by robotic landers, will be necessary precursors to a lunar base. The orbiter can provide detailed altimetric , radar, and photogrammic information required for subsequent landings, while the penetrators can provide insitu measurements of priority deposits at significantly lower cost than propulsive landers. Given the potential economic value of these deposits the execution of these missions may be different than previous NASA sponsored programs. Since the results will have significant economic leverage serious consideration should be given to total mission cost, proprietary information, and mission design. Tradeoffs between orbital and lander/rover payloads will be examined. Some concepts based on Clementine I and II will be presented.

LUNAR HELIUM-3 (^{3}He). Harrison H. Schmitt, P.O Box 14338, Albuquerque NM 87191-4338, 505-823-2616.

Interest in mining the resources contained in the regolith of the Moon has increased steadily during the last decade, particularly since Wittenberg and others [1] first noted that solar helium-3 (^{3}He) exists in this pulverized material [2]. Helium-3 is a potential fuel for a fusion energy alternative for the generation of terrestrial electrical power. Additionally the regolith exists as a potential source of solar wind hydrogen, carbon, and nitrogen compounds, as well as indigenous oxygen and various metals, for use in space [3,4]. Water, in particular, makes up an important by-product with a net lower production cost than possible lunar polar ice.

Mining of the intensely pulverized lunar regolith should have many advantages over most mining challenges here on Earth. For example, in most places of interest, shear strength of the regolith is low, 50–60% of the material is less that 100 μm in particle size, concentrations of large rock fragments are predictable or detectable, and there is no water or vegetation. Further, for any specific mining site, existing and future remotely sensed data can be used for general mine planning [5,6].

On the other hand, our scientific knowledge of the *in situ* volatile chemical components, mineralogical and geochemical makeup, physical properties, surface and subsurface environments, and surface optical properties of the lunar regolith derives largely from measurements on samples returned to Earth by the Apollo astronauts. As a consequence of Apollo sample handling and distribution procedures, major changes to *in situ* characteristics occurred before sample investigators had the opportunity to conduct specific physical and chemical analysis.

The fusion of ^{3}He with deuterium produces large amounts of energy, largely in the form of energetic protons, with only small amounts of radioactive waste due to very low neutron production. Uniquely, the energy of ^{3}He fusion converts directly to electricity at twice the efficiency of existing thermal power plants or even other types of proposed fusion and solar plants.

Although known in lunar materials in concentrations of only 20 to 30 ppb, ^{3}He on the moon is far more accessible than ^{3}He on Earth. the energy equivalent value of ^{3}He relative to \$21 per barrel crude oil is about \$3 billion per metric tonne. The equivalent of 30 metric tonnes would satisfy current U.S. demand for electrical power.

Current budgetary and political trends strongly suggest that acquisition of lunar resources of any nature will require a primarily privately managed and financed venture [7,8].

REFERENCES

[1]Wittenberg, L. J., Santarius, J. F., and Kulcinski, G. L., 1986, "Lunar Source of He-3 for Commercial Fusion Power," Fusion Technology, 10, 167.

[2] Wisconsin, 1996, Resources From Space, Nuclear Engineering & Engineering Physics Department URL: http://elvis.neep.wisc.edu/neep602/neep602.html.

[3] Kulcinski, G. L., and Schmitt, H. H., 1987, "The Moon: An Abundant Source of Clean and Safe Fusion Fuel for the 21st Century," 11th International Scientific Forum on Fueling the 21st Century, 29 September–6 October 1987, Moscow, USSR.

[4] Sullivan, T. A., and McKay, D. S., 1991, "Using Space Resources," NASA Johnson Space Center, 27.

[5] Cameron, E. N., 1993, "Evaluation of the Regolith of Mare Tranquillitatis as a Source of Volatile Elements," Technical Report WCSAR-TR-AR3-9301-1, Wisconsin Center for Space Automation and Robotics.

[6] Schmitt, H. H., Kulcinski, G. L., and Sviatoslavsky, I. N., 1992, "Spiral Mining for Lunar Volatiles," in Engineering, Construction, and Operations in Space III, W. Z. Sadeh, S. Sture, and R. J. Miller, editors, American Society of Civil Engineering, New York, 1162-1170.

[7] Schmitt, H. H., 1994, Lunar Industrialization: How to Begin? Journal of The British Interplanetary Society, 47, 527–530.

[8] Schmitt, H. H., 1997, the Interlune-Intermars Business Initiative, Journal of Aerospace Engineering (in press).

Space Mining

From material prepared by the Colorado School of Mines for the Kola Mining Institute
by William Sharp and Brajendra Mishra (Metals)

"Space resources are incomprehensible - beyond our ability to imagine as we have yet to meet them face-to-face" (B&B - CSM Center for Space Mining)."

The Dream (in the beginning)

"Earth is the cradle of mankind; but one cannot live in the cradle forever (Konstantin Tsiolkovsky)."

The concept of mining the heavens for its riches is a dream held by many individuals throughout the world. It is not a question of if it will happen, but rather when and under what circumstances. ...

Uncertainty and Risk (why space mining?)

"The business executive is by profession a decision-maker... Whether the outcome is a consequence of luck or wisdom, the moment of decision is without doubt the most creative and critical event in the life of the executive (C. Jackson Grayson, Jr. - Decisions Under Uncertainty)."

Like any "profit-oriented" enterprise the minerals industry is in business to produce raw materials and finished products to satisfy human needs. ...

Feasibilty (finding a reasonable scenario)

"The natural forces resulting from mankind's development..., gives rise to us understanding the necessity of human expansion into space as a continuation of civilization's natural progress (Olga Zakharova - Space'90)."

What will be the economics behind the technological development? What need must a resource-base fulfill? The following will suggest a scenarios which might provide a natural need for locating and developing space resources. ...

Resources (the value)

"Space is filled with unbounded resources and inexhaustible possibilities...(Olga Zakharova - Space '90)."

The abundance of resources and the history of the Earth's crust is the foundation of our world as we know it here on Earth. ...

Space Environment (constraints)

" The Earth has survived now for 4.6+ billion years. It may survive for yet another 4.6 billion years. However, mankind as we know it, may not survive the next 100 years (B&B - Whole World Thinking)."

The environment of space presents major design problems for equipment and protecting the fragile human anatomy from unnatural exposures. ...

<u>Delineation</u> (where is the resource?)

"The mining geologist is always pressured to outline new ore deposits and expand those developed. Since he works with rock volumes containing mineral concentrations, he must evaluate not only the actual deposit but also the parameters controlling them within the framework of space and time (L.W. LeRoy - Subsurface Geology, Colorado School of Mines)."

On Earth, mines are considered fixed and classified according to well written laws and regulations. Space resources are continually in motion relative to the Earth. ...

<u>Subsurface Excavation</u> (the cost)

"Many persons hold the opinion that the metals industries are fortuitous and that the occupation is one of sordid toil, and altogether a kind of business requiring not so much skill as labor. But as for myself, when reflect carefully upon its special points one by one, it appears to be far otherwise (Georgius Agricola - De Re Metallica)."

In General here on Earth, large surface excavations move bulk material faster and more cost efficient than smaller underground excavations; however, ...

<u>Technology</u> (making it work)

"Trends, like horses, are easier to ride in the direction they are already going (John Naisbitt - Megatrends)."

The ability to drill, dig, scrape, cut, break, tear, and/or crush material for purposes of sampling a resource or freeing ore from its environment will be the first requirement in any space mining operation. ...

<u>Design</u> (the system)

"Law XXXV - The weaker the data available upon which to base one's conclusion, the greater the precision which should be quoted in order to give the data authenticity (Norman Augustine)."

The final stage in the design of a mine is the integration of all the unit operations into an overall extraction sequence. ...

<u>Conclusion</u> (in the end)

"NEOs represent a new and unknown environment for exploration - in many respects, more tantalizing than the partially explored Moon." (Carl Sagan - to Planetary Society for Dan Goldin)

Cost remains the major deterrent to space mining. ...

<u>Homepage</u>: **http://www.mines.edu/Research/space/mining.shtml**

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MINING THE MARS ATMOSPHERE. K. R. Sridhar, Associate Professor, Aerospace and Mechanical Engineering, Tucson AZ 85721, (520) 621-6111, sridhar@shakti.ame.arizona.edu; John E. Finn, NASA Ames Research Center, Regenerative Life Support Branch, Moffett Field CA 94035, (415) 604-1649, jfinn@mail.arc.nasa.gov.

Vision for Market: This concept will mine the atmosphere of Mars and process it to extract/ generate compressed carbon dioxide, compressed buffer gas mixtures of nitrogen and argon, water, oxygen, carbon monoxide, and/ or carbon. Such products can be of use to science instruments, robotic and human missions. The products can be for utility purposes, life support, propulsion (both interplanetary and on the planet's surface), and power generation.

Products: The products that can be extracted/ generated from the Mars atmosphere and their uses are as follows:

Compressed Carbon Dioxide: Using the diurnal temperature swing on the surface of Mars as the primary source of energy, the relatively low pressure (6–15 mb) atmosphere can be compressed to higher pressures (1–2 bar) using an adsorption/ desorption cycle. Higher pressures and/ or mass throughputs are possible if additional heat (such as waste heat from other chemical processes or power plants) is available. There are several uses for the compressed CO_2 utility gas. In science instruments they can be used to blow dust off optics and instrument interiors, clean specimens, etc. In robotic missions they can be used, among other things, to blow dust off solar panels, inflate panels and structures, give propulsive thrusts to unjam stuck mechanisms, and provide the "feed stock" for propulsion generation plants. In manned missions, the gas can be used for the above applications as well as oxygen generation for life support, and for plant growth chambers. They can also be used as a means of providing the "green-house gas" for an enclosed Mars dome.

Nitrogen and Argon Mixtures: The process that is used to compress the carbon dioxide can be modified relatively easily, with the addition of a separation column, to separate and compress the nitrogen and argon mixture (~4 volume percent of the atmosphere) present in the Mars atmosphere. The gases can be used as a carrier gas in instruments, buffer gas for life support, and as a source of nitrogen for other chemical processes (production of ammonia for example).

Oxygen Generation: Oxygen can be produced from the predominantly carbon dioxide atmosphere by a process called solid oxide electrolysis. In this solid state process oxygen and carbon monoxide are produced from the feed gas of carbon dioxide. Oxygen thus produced can be used for propulsion and/ or life support.

Carbon Monoxide: Carbon monoxide is the byproduct of the carbon dioxide electrolysis process. This "fuel" can be used to advantage for Mars surface propulsion, and as a fuel to operate a regenerative fuel cell in the night, if the electrolysis is performed during the day with photovoltaic cells. In this manner, the same carbon dioxide electrolyzer stack hardware will perform as a fuel cell during the night (an energy storage device with high efficiency).

Carbon: Carbon can be produced by disproportionating the carbon monoxide to produce solid carbon and carbon dioxide. If this process is added to the electrolyzer, the end products of the combined process would be solid carbon and oxygen. Carbon can be used as a fuel, or as valuable carbon fiber that will be used to build reinforced fiber composites.

Water: The small amounts of water present in the atmosphere can be mined using a temperature swing adsorption process. The volume of air that needs to be processed to obtain significant amounts of water is quite high in most locations.

Advantages of the Processes Described: Since the planetary materials required for the above processes come from the atmosphere that is relatively homogeneous, this concept can be site independent as long as it is on the surface of Mars. Most of the processes described here require very little, if any, electrical energy. The primary source of energy for most of the processes comes from the diurnal temperature swing on the surface. Most of the components involved in these processes are solid state, i.e., they have very few moving parts and hence, inherently more reliable. The solid oxide electrolysis technology can be used to extract oxygen in the carbothermal or hydrogen reduction process used for LUNOX from regolith (commonality of technology for Moon and Mars ISRU).

Lunar Materials for Construction of Solar Power Satellites
submitted by
Gordon R. Woodcock

VISION FOR MARKET

Construction of solar power satellites in geosynchronous orbit is supported by production of engineering materials by a lunar industry from lunar resources.

PRODUCTS

Metals, glass, and propellants (hydrogen and oxygen).

PRIMARY CUSTOMER

Electric power generation companies which own the solar power satellites and sell power to electric utility companies.

SECONDARY CUSTOMER

Byproducts are retained on the Moon for use in expansion of lunar industry

ECONOMICS OF MARKET

Prior studies[1] show reduction in Earth-to-orbit transportation by about a factor of 4 if lunar materials can supply 90% of the solar power satellite mass. This can be achieved with ordinary structural materials such as steel, aluminum and glass. If water is available on the Moon in industrial quantities for production of propellants, the factor of 4 increases to the range 6 to 8.

This being the case, space transportation price to low Earth orbit can be as high as about $500/lb. Since cost to the Moon is about 10 X cost to LEO, amortization of lunar investment requires that lunar production equipment be able to produce several times its own mass in useful product each year.

The ultimate market for solar power satellites, assuming they are economic electric power producers, is at least 1000 GWe. The amount of lunar material in construction of these satellites is of order 5 to 10 t per MWe (terrestrial output). This suggests a total aggregate market of order 10 million t of materials at (say) $100,000/t plus delivery charge for a total of one trillion dollars plus delivery charges. Delivery charges can't be more than about this amount for lunar materials to be economic.

Lunar propellant requirements, assuming use of hydrogen/oxygen for delivery from the lunar surface to geosynchronous orbit by way of reusable transportation, are about twice the satellite materials mass, of order 20 million t. Assuming water=propellant this is about 0.02 cubic km of water. Lunar south pole deposits thick enough to be economically recoverable would represent an adequate resource.

Because the cost of supporting people on the Moon will be on the order of thousands of dollars per hour, labor per kg of material can be no more than a few minutes and the entire operation will have to be highly automated and robotic.

NON-ECONOMIC BENEFITS

Byproducts for development of lunar settlements

PRODUCTION OBJECTIVES

Tens of thousands of t per year

TECHNOLOGY NEEDS AND MATURITY

Technologies of production are poorly understood. Steel/iron can probably be beneficiated by magnet and smelted in a solar furnace. Lunar silicates may make decent glass. To what extent beneficiation is required is TBD. Oxygen can be extracted from regolith. If adequate supplies of water ice exist, oxygen and hydrogen may be extracted by electrolysis.

PLANETARY MATERIALS REQUIRED

Regolith, several t per t product. For glass production, lunar rocks may be preferable if higher concentration of desired silicates can be so obtained.

MANUFACTURING AND PRODUCTION

The basic processes should be fully automated (or robotic) with human labor requirements only for maintenance and repair. Once the basic processes themselves are understood this doe not appear to be a difficult technical problem.

POWER REQUIREMENTS

Hundreds of megawatts or more; some thermal, some electric. There appear to be permanently sunlit areas near the lunar south pole. These could be exploited for solar electric power stations and solar furnaces. With no wind loads, very large solar panel installations are practical.

[1] *Solar Power Satellites*, 1993, P. E. Glaser et. Al. Editors, pub. by Ellis Horwood